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Seismology

6956 Seismic Source: TRAVEL TIMES AND STATION CORRECTIONS FOR P-WAVES AT 115 STATIONS OUTSIDE THE UNITED STATES
A. M. McNeill (Department of Geological Sciences, Harvard University, Cambridge, Massachusetts 02138), and D. L. Anderson

Approximately 3300 shallow focus earthquakes and 1000 seismic stations have been used in a study of P-wave travel-time and station corrections, including spherical effects. The results were calculated from a study of 100,000 earthquakes and 1000 stations, having uniform distance and azimuthal coverage were statistically reduced and used to refine P-wave travel times and station corrections. Station corrections are provided for 36 seismic stations.

The station corrections involve three terms: the static effect, the dynamic effect, and the dynamic effect. They result in a general conclusion over broad geographic areas and, where coverage is dense, often show small changes from one geological province to another. The corrections appear to be due to upper mantle anisotropy and they correlate with the travel direction in the crust.

J. Geophys. Res., 88, Paper 28184G

6959 Seismic Source: TOTAL-LENGTH SPECTRA OF FOURTEEN LARGE EARTHQUAKES
P. C. Silver (Geological Research Division, Scripps Institution of Oceanography, La Jolla, CA 92037), T. V. Jordan

Total-moment spectra $M(f) = [M_0^2 / (1 + f^2)]^{1/2}$, where M_0 is the moment tensor, are computed for 14 large earthquakes recorded by the International Deployment of Accelerometers (IDA) network using the new-moment retrieval method proposed by Silver and Jordan (1982). For each event we obtain estimates of M_0 averaged over the ten frequency bands, and the spectral slope α in the low-frequency band (1-10 mHz). Typical M_0 values range from 10^{20} to 10^{22} dyne-cm, and α values range from -1 to -2. Our multiple-band estimates of M_0 are usually consistent with comparable single-band values found by other investigators. From the total-moment spectra we derive the zero-frequency (static) moment $M_0(0)$ and the characteristic source dimension L . The $M_0(0)$ values are in the range 10^{20} to 10^{22} dyne-cm, and L values are in the range 10 to 100 km. The parameter α is generally negative, and its magnitude is related to the source dimension L . The parameter α is generally negative, and its magnitude is related to the source dimension L .

6960 Seismic Source: SOURCE TIME AND SCALING RELATIONS OF LARGE EARTHQUAKES
S. H. Hanks (Department of Earth Sciences, University of California, San Diego, La Jolla, CA 92037), and K. W. Hudnut

Source time is a kinematic fault parameter corresponding to the duration of seismic energy release. It is a function of the size of the fault, the slip, and the rupture velocity. We have determined source times for 100 large earthquakes from the phase of long-period surface waves. Source times are determined for 100 large earthquakes from the phase of long-period surface waves. Source times are determined for 100 large earthquakes from the phase of long-period surface waves.

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6970 Structure of the East and Upper Mantle
J. O. Doser (Department of Geological Sciences, Cornell University, Ithaca, NY 14853), R. L. Anderson, and L. R. S. G. S. G.

This is a special issue paper on the continental crust and upper mantle. It is a special issue paper on the continental crust and upper mantle. It is a special issue paper on the continental crust and upper mantle.

6971 Structure of the East and Upper Mantle
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Walter B. Langbein: 1907-1982



Walter B. Langbein was born in Newark, New Jersey, on October 17, 1907, and died at his home in Arlington, Virginia, on December 10, 1982. For 33 years he carried on a distinguished career in hydrologic research with the U.S. Geological Survey—very much in the public interest.

Langbein graduated from Cooper Union in 1931 with a bachelor's degree in civil engineering. While attending classes in the evening, he worked for the Rosoff Construction Company, beginning as a roofer on a surveying team. At that time the company was engaged by the city of New York to enlarge the subway along 8th Avenue. Between 129th Street and 134th Street, excavation was suspended a short time after it was begun because difficulties were encountered in lowering the groundwater levels with pumps. As the junior member of the engineering staff, Langbein was given the task of measuring and recording the distance of the water level

below a reference mark—a task he later recalled as being his 'introduction' to hydrology.

In 1935, Langbein left the Rosoff Construction Company to take a position with USGS in Albany, New York. He had enjoyed his work with Rosoff and felt he had learned much, although he never understood why Arthur H. Diamond, vice-president of the company, kept urging him to learn about 'least squares'—especially since none of the work called for such knowledge.

He began his hydrologic career in the traditional manner: by stream gaging and making slope-area measurements of floods. The professional atmosphere of the work in Albany made a lasting impression on Langbein: There was no time clock to punch, attention was paid to details, responsibilities were delegated, and one was encouraged to learn. Throughout his career, Langbein sought to provide this atmosphere for others.

It was the hydrology of floods and their social impacts that attracted Langbein's scientific attention. He wrote extensively on the subject, particularly after he transferred to Washington, D.C. in 1939. His technical papers, as well as those written for a more general audience, on the probabilities of floods and the relation of those probabilities to social risks within the flood plains, and his book, *Floods*, coauthored with W. G. Hoyt, directly contributed to the development of a federal position on flood insurance. That position was implemented by the 1968 National Flood Insurance Act (P.L. 90-448; August 1, 1968).

During the late 1940's and early 1950's, Langbein was closely associated with the Soil and Moisture Conservation Program of the Interior Department. He was particularly interested in the effects of grazing and logging on soil moisture and runoff. While associated with that program, he devised a 'tipping-bucket' rain gauge recorder before recording rain gages became available. It was during this time that he also became interested, through Earl Harebeck, in measuring evaporation and transpiration.

Langbein recognized that the runoff from drainage basins and the drawdown of aquifers could not be explained strictly in terms of climatic factors; an account of land use was no less important. To provide a rational basis for quantitatively accounting for land use, he collaborated with Luna B. Leopold in studying the carrying capacities of drainage basins in terms of their geomorphologic features. Together, they gave the first statistical explanations of R. E. Horton's 'laws' of stream orders and of the meandering of rivers. What ever else might be said about this work (carried out in the early 1960's), it gave meaning to hydrology on a large regional and temporal scale. A closer look at this work would do much to further dispel the notion that 'each river is a law unto itself,' a notion that can be traced in the hydrologic literature back to the turn of the century.

From the time he recorded his first 'hydrologic' measurements while working on the construction of the New York City subway system, he never lost interest in matters pertaining to the collection of hydrologic data. In fact, his interest in data collection increased as a younger generation was introduced to hydrology through computer simulation rather than through the gaging of streams and wells. He did not question the merit of this newer introduction, but he was concerned that the quality of the data not deteriorate.

His book, *Water Facts for the Nation's Future*, coauthored with W. G. Hoyt in 1959, drew attention to how important systematic collection of data is to development of water resource systems. The book was the motivation for a comprehensive approach to data collection, now generally referred to as network design, in explicit terms of the economic worth of data. Following the Ottawa meeting of the International Association of Hydrological Sciences in 1960, network design became of prime interest in hydrologic research in addressing questions about the relative importance of parameter estimation and choice of model in describing the stochastic properties of hydrologic processes.

Together with Luna B. Leopold and Ray Nace, he was instrumental in laying the foundation for the International Hydrologic Decade (1965-1975). His active participation did much to assure the success of the 'program' in furthering international exchange in hydrologic research, in promoting a more structured approach to national data collection programs through network design, and in providing a more comprehensive description of the global water balance.

In recognition of his scientific contributions he was the recipient of many awards, among them the Bowie Medal (1960) and the Horton Medal (1976) from the American Geophysical Union, the J. C. Stevens Award (1963) from the American Society of Civil Engineers, the Distinguished Service Award (1959) from the Department of the Interior, and the Warren Prize (1976) from the National Academy of Sciences. A year after he retired in 1969, he was elected a member of the Academy. And in November 1982, he and Professor Korzun of the Soviet Union were the corecipients of the International Prize in Hydrology for 1982, awarded by the International Association of Hydrological Sciences.

Many of us have lost a friend and colleague, one who so often and willingly gave us his technical help and wise counsel. He learned and then taught us much about 'least squares.' We will miss him. Younger generations will make his acquaintance, for his place in the annals of hydrology is secure.

In his honor, a memorial fund for the study of water resources has been established at Cooper Union.

This obituary was written by Nick Malabou, a hydrologist in the Water Resources Division of the U.S. Geological Survey in Reston, Va. He wishes to express his appreciation for material on Langbein's early career which was provided by Rose Langbein and Charles C. McDonald. (Photograph courtesy of the U.S. Geological Survey.)

News

Wet December for Nation's Streams

Much of the nation experienced a very wet December, with 60% of the key index gaging stations in parts of 25 states reporting flows within the highest 25% of record, and record high December flows were set on key index stations in at least 14 states, according to the U.S. Geological Survey.

As a further indication of the wet December conditions, USGS hydrologists said that the combined flow of the nation's 'big five' rivers (Mississippi, St. Lawrence, Columbia, Ohio, and Missouri), which was boosted by runoff from rain-swollen streams, ended the year on a wet note, averaging 1203 billion gallons a day (bgd) during December, almost twice the average for the month and the seventh straight month that flows have been above average.

The intense flooding that affected much of the Mississippi and Missouri river basins boosted streamflow on those rivers to their highest December flows in 55 years of record. Flow of the Missouri River at Hermann, Mo., averaged 117 bgd, 347% above average for December. On the Mississippi River near Vicksburg, Miss., December flow averaged 741 bgd, 142% above average.

In the areas heaviest hit by the flooding, streamflow runoff at many sites set new record highs and the recurrence intervals of flooding in parts of Arkansas, Illinois, Louisiana, and Missouri exceeded 100 years. This means that on the long-term average, a flood of this magnitude is not expected to occur more than once in 100 years.

Indicative of the record-high December discharge in the Midwest was the flow of the Mississippi River at Keokuk, Iowa, which averaged 81.2 bgd during December, the highest December average flow in more than 100 years of continuous records at that site.

In contrast to the many record high streamflows, key index gaging stations in parts of Kansas, Texas, South Carolina, Wisconsin, and a large area of southeastern New

Swiss NSF Fellowships

York reported well-below average streamflow—within the lowest 25% of record. Also in the East, streamflow conditions in the Delaware River basin remain extremely low and drought emergency measures are continuing. Reservoir levels in the basin are still only about 33% of their full capacity.

Swiss NSF Fellowships

The Swiss National Science Foundation (SNSF) annually awards a few international postdoctoral fellowships for American scientists involved in earth, astronomical, atmospheric, mathematical, physical, or engineering sciences to work in Switzerland. Recipients must be under 36 years of age at the beginning of the fellowship tenure.

Applications for fellowships that begin between September 1, 1983, and April 1, 1984, must be completed and returned to the U.S. National Science Foundation (NSF) by February 28, 1983. NSF will then transmit the applications to the Swiss National Science Foundation. Awards usually are announced by SNSF in July.

For application forms and additional information, contact Warren Thompson, Division of International Programs, National Science Foundation, 1800 G Street, N.W., Washington, DC 20550 (telephone: 202-357-9700).

Subject to availability of funds, a few fellowships will also be awarded for tenure beginning between September 1, 1984, and April 1, 1985. Selection procedures are likely to change, however. Interested persons should contact NSF. Applications for these fellowships will be due at NSF by October 3, 1983.

AGU

Radio Science Special Issue

A special issue of *Radio Science* will focus on the topic 'Emissions from particle beams in space.' The scope of the issue will include emissions resulting from both natural and artificial particle beams. Thus topics will include most emissions from planetary magnetospheres as well as from controlled spaceborne experiments such as those performed on the STS-3 shuttle mission.

The deadline for receipt of papers is March 1, 1983.

Submit papers to Erwin Schmertling, Guest Editor, STAR Laboratory/SEL, Department of Electrical Engineering, Stanford University, Stanford, CA 94305.

Meetings

1982 AGU Fall and ASLO Winter Meeting Report



Poster sessions, a growing part of the AGU meetings, are an attractive way for scientists to display their work.

There were more than 2400 papers presented, with more than 3250 attendees registered at the 1982 Fall Meeting in San Francisco. This was the largest AGU meeting ever. Changes to the program and additional, late and revised abstracts are printed below.

Papers Not Presented

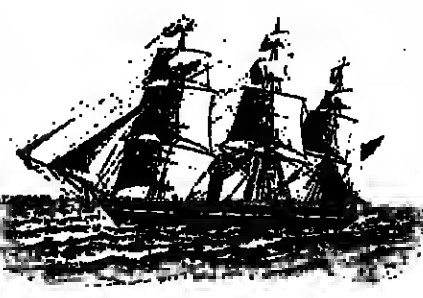
A11A-14, R. L. Gardner et al.; A11A-15, J. W. Erler et al.; A13A-01, W. H. Pollock et al.; G32A-06, P. F. MacDoran; G32A-11, F. Mulargia et al.; G52A-02, B. C. Thompson; G52A-04, J. Helgason; H12A-03, L. Duckstein; H21A-17, D. R. Winesett et al.; H31A-08, D. H. Burns; H41B-04, D. C. Wilkin; H51A-05, G. Padmanabhan; H51A-09, K. L. Verdin.

LO11A-15, G. T. Taylor; LO11B-08, D. W. Krempel; LO11B-08, W. G. Harrison; LO12B-10, J. M. Morrell et al.; LO21A-12, A. M. Menden; LO31B-02, D. Doger; LO31B-14, J. R. Robertson; LO31C-02, D. Waslenchuk and R. Zajac; LO31C-03, M. C. Newman et al.; LO31C-08, A. W. Herman; LO31C-10, P. R. Haberstroh and S. I. Ahmed; LO31C-12, N. T. Sternman and B. B. Freedlin; LO31C-13, R. R. Cohen; LO31C-17, H. A. Vanderploeg; LO31C-22, G. L. Tighmon; LO42A-09, W. K. W. Li; LO52A-12,

A. W. Groeger et al.; LO52A-11, R. L. Whitman; LO52A-12, A. W. Groeger.

O11C-02, N. E. Huang et al.; O11C-15, F. Gonzalez; O11C-14, M. R. Mulhert; O12A-09, P. Ripa; O12C-02, R. W. MacDonald; O12D-08, D. Noe; O12D-14, P. F. Spaul; O12D-15, H. Bryden; O12D-21, A. D. Kirwan et al.; O21A-08, C. Paola; O21C-04, R. H. Fillard; O21D-10, L. Mignard et al.; O21E-08, W. G. Graustein; O22B-06, J. V. Zlot; O22C-05, M. A. Kaminski; O22D-05, E. J. Lindstrom; O22D-12, R. G. Peterson; O22C-11, F. S. Hotchkiss; O22C-16, C. S. Saccetta; O22C-19, J. C. Patterson et al.; O41B-07, C. S. Nelson; O41B-10, R. Iurriaga et al.; O41B-11, J. J. Simpson; O41B-15, R. C. Dugdale and J. J. Macdonald; O51C-30, J. Conde; O52B-06, S. Honjo; O12D-05, E. A. Kelley; P31A-10, A. J. F. Stewart; P31A-6, F. C. Michel; S32-01, J. Cipar and C. Market; S32A-04, D. R. Hutchinson; S32A-09, R. Butler; S72-11, J. A. Cane; S81B-09, P. Scott; S82A-03, J. R. Bowman; S82B-05, R. A. Davis and R. J. Mauk; S12A-02, A. Dasgupta; S12A-02, L. M. Duncan; S12A-13, K. Brunning; S12B-06, K. Wilhelms; S12B-15, M. El-Raey; S14A-02, S. Mesick; S14A-09, H. A. Garcia; S14B-07, H. M. Chang; S14A-09, H. H. Sargent III.

Meetings (cont. on p. 44)



The Oceanography Report
The focal point for physical, chemical, geological, and biological oceanography.

Associate Editor: Arnold L. Gordon, Lamont-Doherty Geological Observatory, Palisades, New York, 10964 (telephone 914/359-2000, ext. 325)

The Manganese Nodule Program

Michael L. Bender

Introduction

The Manganese Nodule Program (MANOP) began in 1977 with funding from the International Decade of Ocean Exploration (IDOE). It replaced an earlier IDOE program that was started in 1972 in part by Maurice Ewing. MANOP's view is that the composition and occurrence of nodules can be best understood in the context of the large variations in the rate of organic matter to the deep-sea floor and the variable sedimentary geochemistry of their environment. Therefore, from the beginning much of MANOP's effort has been directed toward understanding the cycling of the biologically active elements—O₂, C, nutrients, and trace metals—in the deep sea; in fact, this aspect has itself become a primary goal of our work. MANOP is studying manganese nodules and abyssal geochemistry at five varied North Pacific sites (Figure 1). The sites, in order of increasing biological productivity in surface water, are site H, a hemipelagic site in the Panama Basin; site M, a metaliferous site on the eastern side of the East Pacific Rise; site C, a calcareous site at 10°N, underneath the equatorial upwelling zone; site S, a siliceous site, that is nearly a site of non-deposition, with a ~1 in thick cap of Quaternary aluminosilicate sediment overlying Miocene siliceous ooze; and site R, a red clay site north of Hawaii. Manganese nodules are present on the seafloor at sites H, S, and R.

The scope of MANOP is shown in the cartoon in Figure 2. The effort devoted to understanding the cycling of bioactive elements includes determining the particulate flux to the seafloor, the benthic flux of dissolved chemicals across the sediment-water interface, and the burial rates of the bioactive elements. As part of this work, J. Dymond (Oregon State University) and A. Soutar (Scripps Institution of Oceanography) are deploying sediment trap arrays at each of the MANOP sites. The arrays are deployed for a year, and four tri-monthly samples are collected from each trap so that seasonality in the particulate fluxes can be studied. Dymond is analyzing C, CaCO₃, Si, major elements, and trace metals in trap samples. W. Moore is analyzing U-series radioisotopes to study trapping efficiency and scavenging rates of these elements. J. Edmond (MIT) is studying deep water hydro-

graphy and distributions of trace metals at our sites. S. Emerson (University of Washington), and M. Bender and D. Heggie (University of Rhode Island) are studying pore water chemistry to understand the rates and mechanisms of organic matter oxidation on the seafloor and the compositions of pore fluids from which nodule bottoms may grow. The rates of sediment accumulation at each site are being determined by T.-L. Ku (University of Southern California) and D. Kadko (U.S.G.S., Menlo Park) using U-series dating. Rates of sediment bioturbation are being estimated by Ku and Kadko using Pb²¹⁰ and by K. Cochran (Woods Hole Oceanographic Institution) using Th²³² and Pu.

Detailed studies of the marine geology are being done at each of the sites. Each site has been surveyed by Deep Tow (F. Spiess and P. Lonsdale, Scripps) for detailed bathymetry, bottom photography, bottom reflectance, and subbottom reflectors. The bottom reflectance studies, done with side-scan sonar, are particularly interesting, as they give a qualitative picture of nodule abundance variations on the seafloor. At sites S and H, W. Gardner and L. Sullivan (Lamont) have taken bottom photographs over a year-long period. At H, we photographed and surveyed the seafloor with Alvin in 1981. At all sites, R. Heath and M. Lyle (Oregon State University) have extensively studied the major and trace element composition of the sediments.

Studies of manganese nodules are aimed at understanding their growth rates and metal geochemistry. Dymond has studied the compositions of whole nodules as well as scrapings from tops and bottoms. P. Buseck and S. Turner (Arizona State University) are collaborating with MANOP, doing TEM studies of the crystallography of nodule minerals. Moore (University of South Carolina) and Ku have made detailed studies of the uptake of U-series radioisotopes by nodules from seawater, pore water, and sediments. The most extensive effort has gone into determining growth rates of manganese nodules by Th²³⁰ dating, Pa²³¹ dating, and Be¹⁰ dating (the latter by T.-L. Ku of the University of Southern California and E. Nelson of Simon Fraser University).

The MANOP Bottom Lander, our largest single effort, is being constructed by R. Weiss (Scripps) to carry out in situ seafloor experiments bearing on many of the above areas. The Lander is a free vehicle with three box cores; it is designed for seafloor deployments of several months' duration, during which time microprocessor-controlled experiments may be run. During the deployments, circulating pumps of a new design, which have very low power requirements. The water within each chamber can be sampled up to 20 times during the course of the experiment. At the end of an experiment, scoops under the boxes close and cores are thereby retrieved.

Two inaugural experiments are planned for the Lander: benthic flux measurements and radiotracer uptake experiments. In the benthic flux experiments, fluxes of O₂, nutrients, C, alkalinity, and trace metals across the sediment-water interface will be determined from the rates of change of concentrations in the chamber water. In the radiotracer uptake experiments, radio-labeled tracers are added to the chamber, and the distribution of spikes is subsequently determined in the chamber water (as a function of time) and in the sediments and pore water (as a function of depth). The results will give information about adsorption of trace metals by sediments and nodules, of bioturbation, and of irrigation.

MANOP Site H Results: Deep Water Cycling of Bioactive Elements

Rather than try to cover our entire effort, this report will focus on the work at site H. MANOP's most studied station. A brief comparison of results at other sites will follow.

This discussion of site H will start where MANOP started, with the Deep Tow work (Figure 3). The bottom shoals from a depth of 3650 m in the south to 3375 m in the north. The generally smooth rise is interrupted by a series of holes up to about 125 m deep near the center of the survey area. Nodule cover, based on Deep Tow photographs, decreases from about 12% of the seafloor in the south to 3–4% in the north. This smooth decrease is punctuated by the bare patches, remarkable areas up to 500 m wide from which manganese nodules are absent. The existence of these features was detected by the contrast between the intensity of side scan sonar reflections from nodule covered seafloor and bare patches; it has been confirmed by Deep Tow photography and DSRV Alvin observations. The bare patches lie in the center of 2–3 m depressions but are not clearly distinguished from nodule-covered sediment by either sediment chemistry or pore water composition. At this point the origin of bare patches remains an important mystery.

MANOP site H underlies highly productive surface waters; therefore, we were not surprised when our Alvin work revealed that site H is an area of intense benthic biological activity. Anemones, brittle stars, shrimp, holothurians, echinoderms, and other animals are common on the seafloor. The site is crisscrossed with tracks, and more extensive deposits of disturbed sediment are common. These include sediment mounds, "cliffs," and the fairy rings—moats about 0.5 m in diameter, with nodules in moats showing clear evidence of movement by organisms.

There is some evidence that this high organic matter flux drives rapid bioturbation of the sediments. Bioturbation rates of 100–1000 cm²/10³ yr (15–30 times typical pelagic values) were measured in one core by Huh and Ku from Th²³⁰, Pa²³¹, and Pb²¹⁰ distributions. On the other hand, in another core, Pb²¹⁰ gave a rate of 30 cm²/10³ yr [Kadko, 1981], as was modeling by Heath of the distribution of solid phase diagenetic manganese profiles (in which modeling transport of dissolved Mn through pore waters is balanced against transport of solid phase diagenetic Mn).

The rapid flux of organic matter to the seafloor and its mixing into the sediments is reflected in the suboxic pore water chemistry at site H. Pore water chemistry may be best understood in terms of the sequence of diagenetic reactions in sediments (Table 1), which has been shown by MANOP and others to be universally followed [Froelich et al., 1979]. With increasing depth, pore water chemistry is characterized by a NO₃⁻ increase (reflecting O₂ reduction and oxidation of organic N), a NO₂⁻ decrease (reflecting NO₃⁻ reduction), a Mn²⁺ increase (reflecting MnO₂ reduction), an Fe²⁺ increase (reflecting Fe₂O₃ reduction), and a SO₄ decrease and an Fe₂O₃ increase (reflecting SO₄ reduction). Two other reactions are also occurring: Mn²⁺ must be oxidized by O₂ where it goes to zero, and Fe²⁺ must be oxidized by O₂, NO₃⁻, or MnO₂ where it goes to zero.

In site H pore waters (Figure 4), the NO₃⁻ increase, and O₂ consumption, are complete by about 1 cm depth. NO₃⁻ reduction begins at about this depth and continues throughout cores.

Rates of organic carbon oxidation in these reactions, calculated from diffusion reaction models, are given in the following table, along with the rate determined by sediment traps and the burial rate determined from the product of the organic C concentration and the sedimentation rate. At site H,

Organic Carbon Balance at MANOP Site H		
Primary production	1900	
Flux to the seafloor	12	
Oxidized by O ₂	(11.6) (by difference)	
Oxidized by NO ₃ ⁻	0.08	
Oxidized by MnO ₂	0.0 ±	
Buried below 40 cm	0.3	

Units: μmol cm⁻² yr⁻¹.

MANOP Site H Results: Nodule Compositions and Growth Rates

Huh and Ku have succeeded in radiometrically dating one site H nodule, measuring a growth rate of 50 mm/yr, for the top and 60 mm/yr, for the bottom. The age for a nodule with a diameter of 8 cm would thus

TABLE 1. Reduction Reactions in Order of Decreasing Free Energy Yield		
Reaction	Indicator	
O ₂ + 2H ₂ O → 2OH ⁻ + H ₂ O ₂	NO ₃ ⁻ increases	
4NO ₃ ⁻ + 5CH ₂ O + 4H ⁺ → 2N ₂ + 6CO ₂ + 7H ₂ O	NO ₃ ⁻ decreases	
2Fe ₂ O ₃ + 3CH ₂ O + 4H ⁺ → 2Fe ²⁺ + 3CO ₂ + 3H ₂ O	Mn ²⁺ increases	
2Fe ₂ O ₃ + 3CH ₂ O + 8H ⁺ → 4Fe ²⁺ + 3CO ₂ + 5H ₂ O	Fe ²⁺ increases	
SO ₄ ²⁻ + 2CH ₂ O → 2CO ₂ + S ²⁻ + 2H ₂ O	NH ₄ ⁺ increases	

For each reaction, the "indicator" is the chemical whose pore water concentration change is most easily monitored. In O₂ reduction, NO₃⁻ is produced by oxidation of organic N (not shown in the simplified stoichiometry).



Fig. 2. MANOP site H, showing project personnel and their roles.

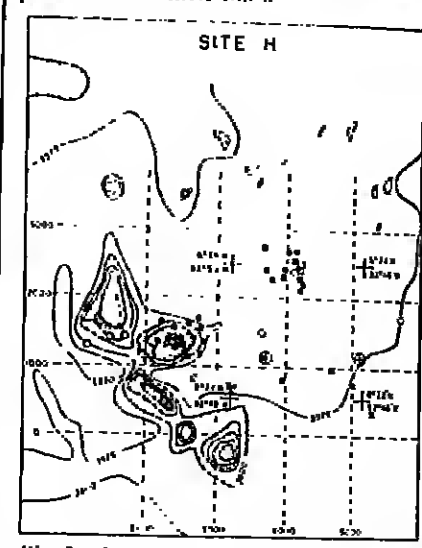


Fig. 3. Bathymetry and coring locations at MANOP site H. Nodule cover increases from ~4% in the north to ~12% in the south. The cross-hatched areas are free of nodules. Boxes and circles represent coring sites.

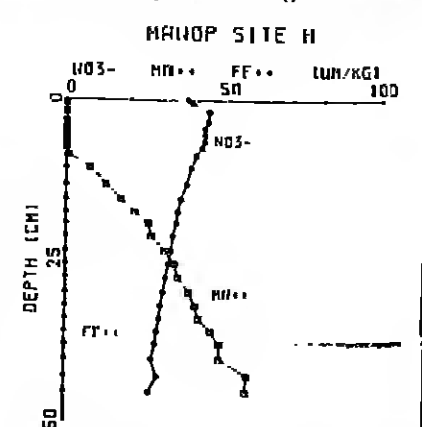


Fig. 4. Pore water chemistry at site H. The changes occurring with depth reflect the sequential reactions outlined in Table 1.

about 2% of the organic carbon reaching the seafloor is buried to at least the depth of the core bottom (~40 cm). Similar amounts of organic carbon are oxidized by NO₃⁻ and MnO₂. NO₃⁻ and MnO₂ oxidation rates vary by about a factor of 2 throughout the site. The results show that nearly all the organic matter reaching the seafloor is oxidized by O₂. The other oxidants, while not important in regenerating organic C, nonetheless are crucial in mediating the amount of organic C (and nutrients) ultimately removed from the system by burial.

As might be expected, diagenetic Mn remobilization has a major influence on the distribution of sedimentary manganese (Figure 5). All cores have a surficial Mn-rich zone 10–20 cm thick, with solid phase Mn concentrations reaching 0.5%. Such a Mn-rich zone forms when Mn²⁺ released to pore waters by diagenetic diffusion into the sedimentary mixed layer, is oxidatively precipitated, and is redistributed by bioturbation. It is noteworthy that the maximum in the solid phase Mn concentration is sometimes well above the depth where pore water Mn²⁺ goes to zero. This feature suggests that some of the solid phase Mn profiles are not steady state features, but reflect from a time when the site was more reducing and Mn²⁺ oxidation occurred closer to the interface.

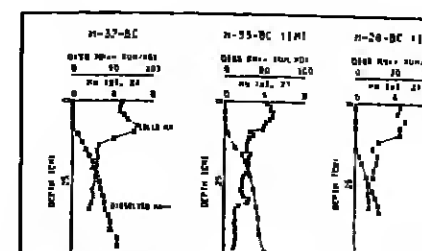


Fig. 5. Pore water [Mn²⁺] (μM/kg) and solid phase [Mn] (weight %) in three cores from MANOP site H. These data record reduction of MnO₂ at depth and upward diffusive transport of dissolved manganese, followed by precipitation at 10–15 cm depth and mixing to the surface by bioturbation.

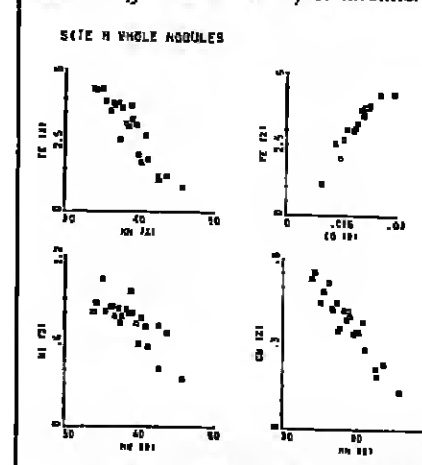


Fig. 6. Scatter plots of the composition of whole nodules at MANOP site H. High Mn nodules are enriched in sedimentary diagenetic manganese. This diagenetic manganese dilutes Cu and Ni.

be about 700,000 yr. The growth rate is very rapid and undoubtedly reflects the supply of diagenetically remobilized Mn.

The Fe, Mn, Ni, Cu, and Co concentrations of whole manganese nodules at site H are summarized in scatter plots in Figure 6. The most striking feature of the composition is the high Mn/Fe ratio. It has long been recognized that high Mn/Fe ratios are characteristic

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Cover. A nearly vertical fracture in the granulite of Lake Edison, Sierra Nevada, California, left-laterally offsets a mafic inclusion and an aplite dike by 8 cm. Structural data demonstrate that this small strike-slip fault nucleated on a preexisting dilatational fracture (joint). Thus this fracture records two distinct deformational events: an extension followed by a left-lateral shear. Strike-slip fault zones with offsets of up to 100 m developed from similar fault faults. From: Nucleation and growth of strike-slip faults in granite, by P. Segall and D. D. Pollard, *J. Geophys. Res.* 88, 555–568.

of nodules underlying highly productive surface waters [Price and Calvert, 1970], and result from the remobilization of Mn²⁺ in sediments by organic matter oxidation, as discussed earlier. How the nodule composition-productivity relationship is mediated, however, remains a mystery. At MANOP site H, manganese is reduced in the MnO₂ reduction zone, between 10 and 20 cm, and is oxidized and precipitated at about 10 cm depth. Hence, Mn diffusion through the oxidized zone to the sediment-water interface is far slower than Mn incorporation into nodules (Table 2). This result shows clearly that nodules cannot grow from upward-diffusing diagenetic Mn²⁺ if our pore water profiles are steady state features. Nevertheless, since the Mn²⁺ concentration rises by 5 orders of magnitude between bottom water and the MnO₂ reduction zone, it is difficult to escape the conclusion that MnO₂ reduction is somehow responsible for the high Mn/Fe ratios of nodules under upwelling areas. But how is Mn supplied to such nodules if not by steady state upward diffusion?

Several possible explanations may be invoked. First, the MnO₂ reduction zone may randomly migrate up and down in the sediment (perhaps in part due to the occasional creation of microenvironments) and, at certain times, be shallow enough to supply Mn to the interface. Perhaps, for example, the MnO₂ reduction zone migrates in response to long time period changes in the forcing functions, such as a change in the sedimentation rate associated with glacial periods. Another explanation is that the depth of Mn²⁺ oxidation may be fixed at about 10 cm, and manganese nodules may be placed at this depth for short intervals by bioturbation, either as a result of being pushed down by animals or being covered temporarily by sediment. Today, about 5% of the manganese nodules are at the Mn²⁺ oxidation depth. We do not know if these nodules are in a short active growth phase or are simply en route to being buried. A third possibility is that the nodule Mn may derive from solid phase oxidized or reduced Mn (e.g., MnCO₃) brought into the Mn-rich zone by bioturbation. This Mn would be transported from the depth of Mn²⁺ oxidation (about 10 cm) to the sediment-water interface by bioturbation. This hypothesis gains plausibility from the recent paper by Pedersen and Price [1982] showing a high level of reduced Mn in solid phases.

Whatever the exact mechanism by which nodules incorporate remobilized Mn, its occurrence has a simple and dramatic effect on nodule composition (Figure 6). Dymond has shown that compositions of whole site H nodules reflect mixing of two end members: a nodule bottom end member incorporating Mn remobilized by MnO₂ reduction and a nodule top end member precipitating from seawater and thought to derive from oxidative diagenesis. The anticorrelation between Mn and Fe in these figures is dictated by simple mass balance but the linear mixing lines for Ni versus Mn, Cu versus Mn, and Co versus Fe can be explained only as end member mixing. The positive covariation of Cu with Fe is expected, since Cu is present in an iron-rich phase; however the anticorrelation between Mn and Ni and Mn and Cu is the opposite of that observed in most pelagic nodules. Cu and Ni in site H nodules are likely found in a Mn-rich mineral; the very low concentrations of these metals in nodule bottoms probably reflects a swamping of pore water Cu and Ni by diagenetic Mn and exclusion from nodules because of their low concentrations relative to Mn in pore waters.

Summarizing our site H results, our detailed studies show that the seafloor at site H has the characteristics which one might expect for a relatively shallow abyssal site underlying high productivity surface waters. A high rate of organic matter sustains a vigorous benthic macrofaunal community and rapid organic matter degradation within the sediments. Nearly all organic matter falling to the seafloor is degraded by O₂ oxidation; oxidation by MnO₂ and NO₃⁻ contributes negligibly to regeneration but is important in mediating the amount of organic C buried and ultimately removed from the system. Sediments are influenced in a number of ways by organic matter degradation, most noticeably by manganese recycling. MnO₂ reduction also supplies manganese to the nodules and leads to very high growth rates, although we are unable to single out the diagenetic Mn transport mechanism. The extensive incorporation of diagenetic manganese into nodules is reflected by the rapid growth rate and high Mn/Fe ratio of site H nodules and the difference between top and bottom chem-

TABLE 2. Growth Rates of Nodules at the MANOP Sites and a Comparison of Manganese Accumulation Rates in Nodules With the Flux of Diagenetic Manganese Through Pore Waters to the Sediment-Water Interface

Growth rate (mm/yr)	Mn accumulation rate (moles cm ⁻² yr ⁻¹)	Diffusive diagenetic flux (moles cm ⁻² yr ⁻¹)
R 0.6–3		
S 5	8 × 10 ⁻⁹	0.01 × 10 ⁻⁹
H 5	70 × 10 ⁻⁹	≈ 2 × 10 ⁻⁹

istry. The top-bottom contrast dominates nodule composition at site H: nodule composition can mostly be explained in terms of mixing two well-defined end members of constant composition.

Comparison of Results at Other Sites

MANOP has retrieved seasonal sediment traps from M and H and annual traps from M, H, and S. Annual near-bottom total particulate fluxes at M and H are similar; at S the value is about a factor of 5 lower (Table 3).

TABLE 3. Summary of Organic C Fluxes at MANOP sites M, H, C, and S

	Site			
	M	H	C	S
Flux to seafloor	12	12	1.8	
Oxidized by				
O ₂	(10.2)	(10.6)	19	1.6
NO ₃ ⁻	1.1	0.08	0.08	
MnO ₂	0.15	0.06	0.01	
Fe ₂ O ₃	0.014			
SO ₄	0.15		2.3	
Buried below 40 cm	0.4	0.2	0.2	0.01

Among these four sites, pure water chemistry changes such that pore water profiles are progressively stretched out as organic matter rain rates fall (Figure 7). That is to say, the flux of organic matter reaching the seafloor decreases, zones in which the various oxidants are consumed occur deeper within the sediments. Only when comparing sites M and H does this generalization fail. Fluxes to the seafloor are similar at these two sites, but the redox zones are much closer to the sediment surface at M. The sites differ in that M has a higher sedimentation rate, while nodules are present at H. More intense diagenesis at M may reflect more burial of organic matter due to the faster sedimentation rate [e.g., Muller and Suess, 1979]. Alternatively, it might be that more organic matter is oxidized before burial at H because nodules allow a more vigorous benthic community to exist; if so, nodules must have a major and heretofore unsuspected impact on sediment geochemistry.

The solid phase Mn distributions at M, H, C, and S are similar to what is expected from the pore water Mn²⁺ gradients discussed earlier. At M and H, the depths of pore water Mn²⁺ oxidation are within the sedimentary mixed zones, and there accordingly are MnO₂ bands near the sediment-water interface. The depth of MnO₂ reduction is closer to the interface at M, and the Mn-rich layer is thinner. At C, Mn²⁺ oxidation occurs at about 20 cm depth, probably just below the mixed layer. The solid Mn distribution is thus characterized by a discrete Mn-rich layer centered at the depth of Mn²⁺ oxidation. At S, where there is no pore water evidence for MnO₂ reduction, and at R, where pore waters are also assumed to be oxidizing, there is nevertheless a sediment surface zone in which Mn is slightly enriched. The origin of this feature is unknown.

Key features of nodule composition at sites H, S, and R are summarized in Figure 8, and growth rate data is given in Table 2. The most striking result is the high growth rate and Mn/Fe ratio at site H compared with the other two sites; these features reflect the supply of diagenetic Mn from the underlying sediment. It is more difficult to understand why, if there is no MnO₂ reduction at site S, the Mn/Fe ratio of site S nodules is higher than that at R. Dymond has argued that metals in site R nodules are primarily hydrothermal; that is, they are derived from precipitation out of seawater. Site S nodules are thought to have a diagenetic Mn component that derives not from MnO₂ reduction but from Mn released from sedimentary ferromanganese hydroxides when Fe reacts with biogenic SiO₂ to form nontronite [Lyle et al., 1977]. Since both R and S nodule bottoms are richer in manganese than tops, the hydrothermal and oxidative diagenetic components are thought to supply metals at both sites, with the oxidative diagenetic component being greater at S.

At site S, the upward manganese flux at the interface, calculated from the pore water concentration gradient, is 3 orders of magnitude less than the rate at which manganese is assimilated into growing nodules. Therefore, another source of manganese is required, and this is believed to be solid Mn released very close to nodule surfaces as a result of the oxidative diagenetic reactions discussed earlier.

Thus, while we confirm the increase in nodule Mn/Fe ratios with increasing productivity, our work supports the mechanism proposed by Lyle et al. [1977] and indicates that this relationship is mediated in ways very different from that envisioned by earlier workers. In oligotrophic waters and upwelling boundary waters (as at site S), productivity increases nodule Mn/Fe ratio by providing diagenetic dissolved Mn²⁺ but by providing SiO₂, which sequesters Fe and releases Mn to nodules in an oxidative process. In higher productivity waters, where the Mn²⁺ oxidation zone is close to the interface, incorporation of dissolved diagenetic Mn²⁺ is possible.

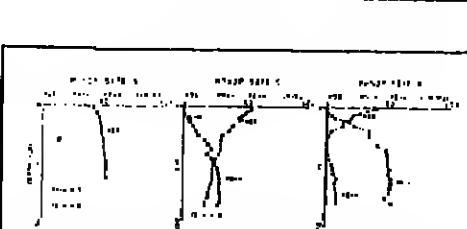


Fig. 7. Summary of pore water concentrations of the redox indicators at MANOP sites S, C, and M. Again, chemical changes reflect the reactions outlined in Table 1.

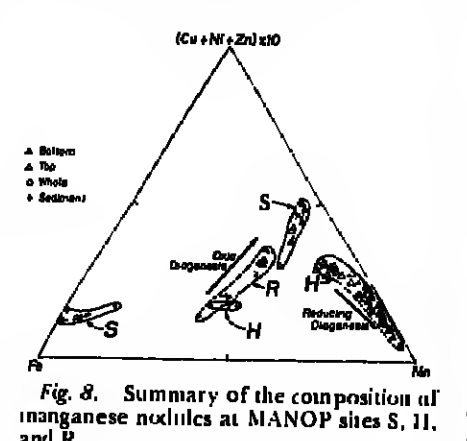


Fig. 8. Summary of the composition of manganese nodules at MANOP sites S, H, and R.

ble only if nonsteady state conditions are invoked. If we assume steady state and growth of nodule bottoms at the interface, the very high Mn/Fe ratios of nodule bottoms at site H must be due to incorporation of solid diagenetic Mn mixed up by bioturbation from the Mn²⁺ oxidation zone.

It has been widely demonstrated that, among pelagic nodules, Cu, Ni, and Zn concentrations increase with increasing manganese. At sites S and R this relationship is followed, but when comparing whole nodules from one site to another and when comparing tops and bottoms at the same site, at H the trend is reversed, for reasons discussed earlier.

In summary, sediment fluxes to the seafloor decrease in the same order as surface productivity (M > H > C > S). As productivity drops, redox zones in the pore waters are spread out to greater and greater depths. At the two high productivity sites, Mn is remobilized and oxidized within the sedimentary mixed zone, forming a Mn-rich layer near and at the interface; at site C, Mn is remobilized and oxidized just below the mixed zone, forming a discrete Mn maximum, and at site S the MnO₂ reduction zone is not penetrated by our cores.

Nodule growth rates and Mn/Fe ratios increase with increasing organic matter flux to the seafloor. (Ni + Cu + Zn) increases with increasing Mn until productivity becomes very high, at which point the trace metals are drowned out by Mn and their concentrations in nodules drop.

References

- Froelich, P. N., G. P. Klunkhammer, M. L. Bender, N. A. Luedtke, G. R. Heath, D. Cullen, P. Dauphin, B. Harnmann, and V. Maynard, Early oxidation of organic matter in pelagic sediments of the Eastern Equatorial Atlantic: Suboxic diagenesis, *Geochim. Cosmochim. Acta*, 43, 1075–1090, 1979.
- Kadko, D. C., A detailed study of the uranium series nuclides for several sedimentary regimes of the Pacific, Ph.D. dissertation, Columbia University, New York, 1981.
- Lyle, M., J. Dymond, and G. R. Heath, Copper-nickel-enriched ferromanganese nodules and associated crusts from the Bauer Basin, northwest Naama Plate, *Earth Planet. Sci. Lett.*, 35, 55–64, 1977.
- Muller, P. J., and E. Suess, Productivity, sedimentation rate, and sedimentary organic matter in the ocean, 1. Organic carbon preservation, *Deep Sea Res.*, 26A, 1347–1362, 1979.
- Pedersen, T. F., and N. B. Price, The geochemistry of manganese carbonate in Panama Basin sediments, *Geochim. Cosmochim. Acta*, 46, 59–68, 1982.
- Price, N. B., and S. E. Calvert, Compositional variation in Pacific Ocean ferromanganese nodules and its relationship to sediment accumulation rates, *Mar. Geol.*, 9, 145–171, 1970.

News & Announcements

Glomar Challenger Finds Ophiolite

Deep Sea Drilling Project (DSDP) hole 504B located in the eastern equatorial Pacific, 201 km south of the Costa Rica Rift (CRR), is unique in several ways. Hole 504B extends 1.35 km below the seafloor, which is at a depth of 3.46 km; it has penetrated seismic layers 2A, 2B, and part of 2C and for the first time has provided a very complete section; and it has bottomed in what has been interpreted as a true ophiolite complex. These results constitute for the first time long awaited confirmation of accepted models upon which most oceanic crust theory has been based.

